1 Foreword

Perhaps the most remarkable aspect of evolution is its ability to generate cooperation in a competitive world. Thus we might add "natural cooperation" as a third fundamental principle of evolution beside mutation and natural selection.

– Martin Novak
Five Rules for the Evolution of Cooperation

1.1 Motivation

I firmly believe that the best way to get on is by cooperation. The story of science is often told through the triumph of great geniuses or singular breakthroughs. But, most science is done in teams. This could be in projects like the LHC in CERN, involving thousands of different scientists and engineers from all over the world, or several teams working on small aspects of the same research or in the team of largely uncredited deaf women who were responsible for tracking and cataloguing stars under Edwin Hubble. Even above being a "team game", science is in itself a great shared reality, based on observations and measurements. This, in turn, is based on a shared philosophy, the scientific method: hypothesis, testing and falsification. To construct this shared reality and effectively share their ideas and receive feedback, scientists share their work through written publications and spoken presentations, containing diagrammatic representations of data and concepts[1]. However, scientists working in teams mostly communicate by talking to each other within their research communities[2].

When talking to one another about science, a specific vocabulary is needed. This vocabulary too is co-constructed. This was made very apparent to me when I joined a largely German-speaking laboratory in Munich during my Master's studies. When laser beams in the laboratory needed to be aligned, the German speaking members of the team would not use the German word "ausrichten" to talk about alignment. Instead, as there were a large number of non-native speakers in the international team, the made-up word "alignen"[3] would be used by the whole team, to facilitate understanding. Depending on who was operating the laser, they would need to align something specific, for their experiment. So, depending on who was saying they were going to align the laser, it would mean a different concrete set of actions achieving the same thing: alignment. This throwaway example allows us to see the adopted use of a specific word in a single context, used to mean subtly different things. Not to mention if I was talking to the same people about different topics, then the word alignment could mean something totally different, e.g. politically aligned or alignment in a role-playing game[4].

However, it is not always the case that scientific language enables accessibility. In fact, it can have quite the opposite effect. The everyday word that is used to discuss household electricity in English and German are "power" and "Strom" respectively, the literal translation of "Strom" into English is "current". Learners continue to use both "power" and "Strom" in the context of science lessons when they are not appropriate and associate them with similar misconceptions[5]. For this reason we

[1] There are of course other incentives to do these things, as they garner prestige and a kind of scientific social capital.
[2] There is often considerably less social capital at stake in these kinds of interactions, which can indeed make them more informal and more effective!
[3] Simply the English verb align with German conjugation rules
[4] For the uninitiated, whether your character is good or evil or follows the rules or not.
[5] A discussion of what misconceptions are, how they work, other names for them and

need to make our scientific vocabulary accessible to our learners, if we want to strive for equal and effective education. Science educators cannot also ignore the fact that they are introducing learners to a culture of science. This includes its language and despite the temptation to have a separate scientific language that engages with abstract thought, learners must be exposed to all given words in a variety of contexts and meanings must be made explicit and related to their context.

Using this language in productive classroom talk comes with its own benefits. Students participating in a talk rich curriculum have improved outcomes across the core subjects in primary school[6]. A famous example of the power of student talk to improve learning progress in Physics, comes from the world of higher education with Peer Interaction[7]. Here, undergraduate students engaged in discussions during their contact time, increasing their conceptual understanding. An example of this kind of intervention in lower secondary electricity, however, was not as successful in increasing learning outcomes[8].

With these thoughts in mind, I wanted to go about designing and assessing learning materials that would benefit practitioners and learners alike and be confident in making my recommendation (or otherwise!) of them, but not be solely driven by testing outcomes.

Things did not go exactly to plan. Working across borders in schools, during a global pandemic, as the UK tries to figure out how to leave a customs union that you want to bring 30 iPads from, is not an experience I would recommend. Nonetheless, the following is the collection of ideas, results and analysis collected over those very enjoyable, nearly six years.

how to try and combat them see Chapter 2.

[6] Jay et al. [2017]

[7] Mazur [1997]

[8] Ruthven et al. [2017]

2 *Theory and Measurement of Learning and Knowledge*

You see my physics students don't understand it...
That is because I don't understand it. Nobody does.

– Richard Feynman
QED: The Strange Theory of Light and Matter

Chapter Contents

2.1 Models of Learning and Knowledge 7
2.1.1 Piaget's Mental Representations 8
2.1.2 Vygotsky's Social Learner 8
2.1.3 Rogoff's Learning in Cultural Context 10
2.1.4 The Learner as Agent of Change 12
2.1.5 Self Determination Theory 13
2.1.6 Representations, Analogies and Models both Mental and Scientific 14
2.2 Conceptual Change 18
2.2.1 Rational Conceptual Change 19
2.2.2 Theory Theory 20
2.2.3 Framework Theory 21
2.2.4 Ontological View 22
2.2.5 Knowledge Analysis and Knowledge in Pieces 25
2.2.6 How Theory Informs Practice 29
2.3 A Summary of Alternative Conceptions on the Subject of Circuit Electricity 31
2.3.1 The Physical Model for Lower Secondary 32
2.3.2 The Cluster Concept Electricity† 33
2.3.3 Misconceptions Relating to Current and possibly to wider Electricity† 34
2.3.4 Misconceptions Relating to Voltage 38
2.3.5 Other Difficulties 41
2.3.6 Considering Underlying Schemata 46
2.3.7 Language Resulting in Alternative Conceptions 46
2.4 Measuring Alternative Conceptions and Learning Gains 49
2.4.1 Alternative Conceptions as Distractors and Something Measurable 50
2.4.2 Tests on the Topic of Electricity 51

In this Chapter, I will begin by giving an overview of relevant learning theories, paying special attention to definitions needed in this chapter and beyond. As is generally the case, the chapter will develop from general to specific, from descriptions of knowledge and learning intended for general use to specific learning challenges faced in the teaching of science, specifically physics, and then even closer, on the topic of electricity, the topic of the intervention study in this thesis. The chapter concludes with a review of the literature on the specific alternative conceptions on the topic and the available concept knowledge test on the topic of electricity.

2.1 *Models of Learning and Knowledge*

Models of learning and knowing within Western philosophy date back to Aristotle's analogy of the mind as a blank slate waiting to have ideas etched upon it[9]. These have been developed throughout history and have become progressively more complex with focus on different aspects of the learners' development, with key contributions, that will be discussed in the opening to this chapter from developmental and cognitive psychologists such as Piaget, Vygotsky and Rogoff. Furthermore, there are science education specific contributions to models of mental organisation and cognitive change from educational specialists, such as Vosniadou and diSessa. The idea in this chapter is not to evaluate and critique these models of learning and cognition, but to introduce definitions[10] and use the ideas present within them to inform thinking about how to best support teaching and learning within the context of lower secondary physics, on the topic of electricity. These ideas go on here and in later chapters to inform the rationale and decision making processes involved in developing materials as discussed in Chapter 4. Where models, however, may might make contrary suggestions for practice, this is discussed.

[9] Smith [2014]

[10] Those who read this with a background in the learning sciences will probably be familiar with the ideas contained in this section. I present this here to be an introduction to those with background in physics, from a more "practical" teaching background or for readers who come from a different cultural context.

2.1.1 Piaget's Mental Representations

Schemata describe "figurative representations"[11], suggesting a type of mental image, for clustering and discriminating objects into particular classes or groups. These groupings have underlying rules and rest upon generalisations. The schema are constructed and adjusted by attempted *assimilation* of new ideas into pre-existing schemata and the *accommodation* of small changes to these schemata[12] where inconsistencies lead to cognitive *dissonance*[13].

Schemes are, similarly, mental representations, but this time for procedural knowledge, i.e. how to do certain tasks. This study is primarily concerned with developing figurative knowledge, however the scheme of work implemented introduces some procedures for analysing electric circuits. More nuanced descriptions of the way learners' mental structures are conceptualised are given in Section 2.1.6, as developing and measuring these is the centre of my study. However, just conceptualising them in this primarily rational way ignores the social dynamics important for an intervention centred around peer work.

2.1.2 Vygotsky's Social Learner

The importance of social interaction is central to Vygotsky's work and, although Piaget does not ignore its importance[14], it is not central in his writings. As the current study will implement discussion work in pairs, exchange in this *intermental* space[15] is central. Learners too not only construct ideas together, but in expressing their ideas through *externalisation*[16], mediated by *psychological or cultural tools*, they develop whatever (nascent) thoughts are present[17]. Learners then have the

[11] Siraj-Blatchford and Siraj-Blatchford [2010, p. 209]
[12] Piaget [1929] in Goddu and Gopnik [2022]
[13] Piaget [1929] in Adcock [2012]
[14] DeVries [1997]
[15] A social space for ideas between people.
[16] Piaget also illustrates an internalisation/externalisation dynamic, but on an operational level, with the identification of object surface features being mapped onto how the object may be used and causal constructions, for more see Martí [1996].
[17] Vygotsky [1986]

opportunity to become aware and reflect on their own ideas before interacting with *externalisations* from their partners, which, in turn, they may *internalise*, in a transformative process[18], after their negotiation in the *intermental* space[19].

Another key idea that will be important throughout this work, with regards to both technology and language, is the mediated nature of thinking and idea exchange through *psychological or cultural tools*, also called *signs* or *symbols* under which Vygotsky includes: "language; various systems for counting; mnemonic techniques; algebraic symbol systems; works of art; writing; schemes, diagrams, maps, and mechanical drawings; [and] all sorts of conventional signs"[20]. The idea of a *psychological tool* when looking at language, diagrams and technology will be especially key in my study. Vygotsky argues that usage of *psychological tools* result in new ideas, so in developing tools for classroom use it is important to ensure that these are conducive to the knowledge we wish to construct. For example, through careful use of language and analogy or in the production of diagrams or learning workflows, as discussed in Chapter 4. It is also of note that these tools are not inherent, and must too be learnt.

The Zone of Proximal Development defines the difference in what a learner may achieve when engaged in an activity alone, and when "under adult guidance or in collaboration with more capable peers"[21]. Their partner or guide enables the learner to generate and co-construct novel ideas and solve previously unsolvable problems. Learners can then *internalise* this and then be able to tackle similar activities alone. This, however, beyond Vygotsky, is also possible when the peer is not "more capable", i.e. neither peer can solve the problem alone. For

[18] Vygotsky and Luria [1930/1994] in Lawrence and Valsiner [1993]
[19] Vygotsky [1981b] in translation from Выготский, Лев Семёнович. Развитие высших психических функций: из неопубликованных трудов. Москва: Издателство Академии педагогических наук РСФСР, 1960.
[20] Vygotsky [1981a, p. 137] in translation from the same Russian source.
[21] Vygotsky [1978, p. 86]

example, a well detailed illustration of idea generation and convergence on the scientific principal of this nature is given in a secondary science context in Heeg et al. [2020]. This idea is relevant in that it helps us conceptualise the role of external support enabling the learner to develop, rather than this being modelled by some innate stages.

Beyond Vygotsky's ideas, the nature and extent to which this guidance is provided can be described using the metaphor of *scaffolding*[22]. The guidance suggested includes "recruitment of the child's interest in the task, establishing and maintaining an orientation towards task-relevant goals, highlighting critical features of the task that the child might overlook, demonstrating how to achieve goals and helping to control frustration."[23] These are reflected on in Chapter 4 on the development of teaching and learning materials, for example, through embedding physical contexts, prompting the learner through tasks and implementing a scheme of work and questioning in ways that slowly increases in difficulty. One caveat to this being that the teacher must play a role in all mediation of this kind as well. However, this aspect does not form the locus of interest in this study, with the principles of *scaffolding* being examined more through the teaching and learning resource provision, both analogue and digital - with special consideration being paid to digital affordances and peer learning. The adult role will be discussed, in the way in which technology can empower teachers to assess the outcomes of peer talk, enabling them to make small group or whole class level interventions depending on the outcomes. Empowering the teacher to intervene when necessary, whilst respecting learner autonomy.

2.1.3 Rogoff's Learning in Cultural Context

Whereas Vygotsky primarily looks at dyads, Barbara Rogoff emphasises the cultural nature of learning as a child's "apprenticeship in thinking" with adults or peers in a variety of group structures, her central concern is illustrated well in her own words:

[22] Wood et al. [1976] in Wood and Wood [1996]
[23] Wood and Wood [1996, p. 5]